Title

The choice of path to resilience is crucial to the future of production forests

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Resilience in production forests can be achieved through natural ecological processes or repeated intensive interventions. We caution that the 'coerced' resilience derived from human inputs may exacerbate biodiversity loss, narrow the range of ecosystem services provided, and limit general resilience, i.e. the capacity of production forests to recover from unforeseen disturbances.

Efforts to ensure that production forests provide their intended benefits despite climate change and other stressors are often framed in terms of enhancing the resilience of these systems. Ecological resilience can be defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks"[1]. In forest ecosystems, 'ecological resilience' arises from ecological processes and feedbacks and is frequently related to biological diversity[2]. However, production forests are social-ecological systems which may be heavily and repeatedly altered by human actions. These actions commonly standardize or minimise the forests' intrinsic variability in tree species composition, structure and function, thereby supporting the repeated and predictable delivery of a few desired outputs. As the ecological processes and feedbacks of natural forests are replaced, these systems may become dependent on anthropogenic intervention to be resilient. Here, we argue that pursuing this 'coerced resilience' [sensu [3]] will have ramifications for forest biodiversity, ecosystem services, and the capacity of production forests to recover from unforeseen disturbances (Fig. 1).

Two different pathways to resilience

The effective management of production forests requires decision makers to mitigate the risks of damage from disturbances. The solutions proposed to achieve this often rely on repeated anthropogenic inputs, such as the planting of single or few disturbance-resistant species of seedling, introduction of non-native tree species, use of chemical or mechanical treatments to limit damage from herbivores and pathogens, and removal of competing vegetation and deadwood. The degree to which such human input is used determines whether the result can be classed as ecological or coerced resilience (Fig. 1). For example, forest managers may reduce pathogen risk either by planting pathogen-resistant clones of a desired tree species (coerced resilience) or by adopting mixtures of species which are less vulnerable in combination (ecological resilience). Other human actions that can promote forest resilience include active interventions to reduce stand exposure to risk (e.g. shorter rotations), contain hazards (e.g. 'sanitation' felling of sick trees) and directly reduce tree susceptibility to disturbance (e.g. through tree breeding). In the most intensive form of production forest management, trees are planted as even-aged monocultures and ongoing anthropogenic interventions aim to keep the stand on a deterministic developmental pathway from stand regeneration to final harvest.

Even highly modified and simplified production forests can, through intensive anthropogenic efforts, retain their identity and function after disturbance – for example, by replanting the same tree species after large-scale canopy dieback. However, active and repeated efforts to limit a forest's natural variation in tree species and structure can limit the ecological foundations of resilience, such as complex canopy structures, heterogeneity in tree age and size, and presence of tree species with different functional traits[2,4]. In other words, interventions aimed at maximising coerced resilience may prevent the development of those features which make forests ecologically resilient to disturbances. In response to escalating disturbances, forest managers and society in general are increasingly being faced with choices that involve deciding between ecological resilience and coerced resilience in production forests.

Figure 1. **Ecological versus coerced resilience in production forests**. **a**, For production forests located on the left-hand side, system resilience is primarily conferred by ecological processes, providing ecological resilience. Towards the right-hand side, anthropogenic inputs increasingly determine system resilience, and thereby result in coerced resilience (panel modified from ref [[3]]). **b**, Proposed solutions to disturbance and climate change adaptation efforts can rely to a greater or lesser extent on ecological or coerced resilience to achieve system stability. For example, rotationally clear-cut even-aged, planted stands, dominated by a single species of native or non-native conifer, are typical of many wood production forests. Production forests in this category are often deemed susceptible to a range of abiotic and biotic

disturbances, for which highly contrasting solutions are advocated as effective responses, as illustrated here with five examples. **c-e**, The choices taken have implications for the key drivers of habitat availability in production forests (**c**), the specific combinations and portfolio of ecosystem services provided (**d**), as well as the known and unknown disturbances the production forest is resilient to, and whether general versus specified resilience is achieved (**e**).

Implications of the resilience path chosen

The choice of resilience pathway strongly affects biodiversity, since it alters the primary determinants of habitat availability in production forests. These determinants include tree species composition and disturbance regimes, as well as the resulting forest structures (large old trees, coarse woody debris) and heterogeneity thereof (Fig. 1.C). For instance, if more frequent management cycles are adopted in response to abiotic or biotic disturbances (e.g. shortened rotations in response to pathogen or windthrow risk), forest biodiversity is likely to decline due to the reduced availability of key habitat structures and lowered stand heterogeneity. These impacts can be expected to worsen if combined with sanitation felling or chemical treatments, as in response to e.g. bark beetle outbreaks. In contrast, increasing abiotic and biotic disturbances can motivate the conversion of, for example, even-aged conifer stands to more functionally and structurally complex broadleaf-conifer mixtures, or uneven-aged management, both of which increase the range of environmental conditions and resources provided for biodiversity. Differences in the habitat provision of production forests matter, because one third of the world's forest area is managed primarily for wood production[5]. Moreover, the consumption of primary processed wood products is expected to grow almost 40% over 2020 levels by 2050[6], and less than 16% of the world's forests are formally protected for biodiversity conservation[7]. Thus, global forest biodiversity conservation strongly depends on production forests, whose taxonomic, functional and structural diversity components are at risk from decisions that rely on coerced over ecological resilience.

Over-reliance on coerced resilience will also have implications for the breadth of ecosystem services provided by production forests Fig. 1D; see [8]. For example, rotation lengths in even-aged conifer monocultures can be shortened to help mitigate the risks of windthrow and specific categories of pest and pathogen damage, but this can come at the cost of other forest ecosystem services (including roundwood, wild fruit and mushroom production, water quality and soil nutrient retention, and cultural services involving aesthetic and recreational values[9]). There are thus potential trade-offs for forest managers attempting to coerce resilience in even-aged monocultures solely by increasing the frequency of harvest. In contrast, diversifying the tree species composition can reduce certain abiotic and biotic risks while also increasing the range of ecosystem services provided[8,10].

Specific or general resilience

A primary consideration when seeking to enhance the resilience of forest systems is whether the measures targeting particular disturbances would also be effective at limiting the impacts of other foreseen and unforeseen disturbances (Fig 1.E) – in other words, whether general resilience is achieved, or resilience is limited solely to a specific disturbance[11]. Increasing the resilience of a system to specific disturbances may even cause the system to lose resilience to other types of disturbance[12]. For instance, shortened rotations may increase other risks, including risks from regeneration pests and fungal pathogens causing foliar and stem diseases[9], as well as increased fire risk, which has additional negative outcomes for forest carbon storage[13].

In contrast to resilience to a specific disturbance, general resilience is particularly sought as a strategy for adaptation to climate change, as it involves creating natural-resource systems capable of absorbing the uncertain impacts of even novel disturbances (for instance, future droughts in regions not historically prone to drought)[11]. Environmental uncertainty should now be a central consideration in production forest management, because climate and disturbance regime changes are so rapid and uncertain as to overtake the development cycle of a single rotation, and operate well outside the historic range of variability. Whereas intensified forestry practices can be used to achieve specified resilience, the same interventions cannot be expected to enhance biodiversity. In contrast, production forest management actions that enhance biodiversity and ecosystem functioning also tend to confer ecological resilience[8,10], which in turn begets general resilience.

Resilience for the future

There are limits in the extent to which forest systems can absorb novel disturbances. For example, climatic change is already accompanied by significant increases in abiotic and biotic disturbance impacts on European forests[14], with the expectation that damage from wind, fire, native and non-native insects and pathogens will continue to increase this century. Similar alarms are being raised regarding the future health of the world's forests[15], and these concerns are compounding as global emissions continue to exceed the climate change mitigation targets agreed to under the Paris Agreement. Under such circumstances, the magnitude of environmental change in some regions will likely exceed the adaptive capacity of local tree species and ecological processes, resulting in increasing reliance on assisted migration to try to maintain tree species diversity, and a more general shift to novel forests and – in some areas – even non-forest systems. Rapidly mitigating climate change will help ensure a future where the enhancement of ecological resilience continues to be a viable option in most production forests. The choices taken and the extent of reliance on coerced versus ecological resilience will have repercussions throughout the coming century.

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Competing interests statement:

The authors declare no competing interests.

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